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(Statement A)

Interactions within a Cluster of Low Power Hall Thrusters

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Abstract

We discuss the appearance of an anode current transient which persists a maximum of 500 seconds and results in a 50% increase in the anode current during initial start-up following exposure to ambient laboratory conditions. The anode current transient is characterized by 18 kHz main discharge on/off behavior. This contrasts with the steady state behavior of a strong DC component overlaid with a low amplitude 25 kHz component. Conduction through the radial magnetic field appears to be modified during the transient period. The main discharge chamber is determined to be the source of this behavior. The anode current transient appears to be a result of water absorption on the surface layer of the boron nitride insulator. We speculate as to the connection between the absorption of water and the anode current transient. The modification of the secondary electron emission coefficient could affect near wall conductivity and produce the measured effects. The introduction of hydrogen from dissociated water could also produce these enhanced oscillations.

Introduction

Unlike ground testing, Hall thrusters manifested on spacecraft do not generally use a separate mass flow controller. Rather, the main discharge (anode) current is used in a negative feedback loop to throttle the propellant to the Hall thruster. Therefore if the current is anomalously high for a particular flow rate, the closed loop system will regulate the main discharge current by reducing the flow to the anode and cathode. This will unknowingly reduce the thrust and impulse from a short duration firing. For this reason, understanding the characteristics of this anode current start transient is important for missions where short duration initial firings are necessary.

Apparatus

These measurements were taken in Chamber 6 at the Air Force Research Laboratory (AFRL) Electric Propulsion Facility at Edwards AFB, CA. Chamber 6 is a stainless steel chamber with a 1.8 m diameter and 3 m length. It has a measured pumping speed of approximately 32,000 l/s on xenon. Pumping is provided by four single stage cryo-panels (APD single stage cold heads at ~25 K) and one 50 cm two stage APD cryo-pump (<12 K). The chamber is roughed by a oil free Stokes Stealth® mechanical and blower. The chamber is

configured such that the 50 cm cryo-pump may be isolated from the chamber and cryo-panels. During the pump down of the chamber, the chamber is first roughed to approximately 30 mTorr (N_2) using the mechanical and blower pumps. At this time, the cryo-panel cooling begins.

The thrusters used for this test are four BHT-200-X3 thrusters which are described in detail elsewhere [1,2]. This is a cluster of four 200 W thrusters being tested to determine the engineering aspects of clustering higher power Hall thrusters on a single spacecraft [3-4]. The cluster of four thrusters is shown in Fig. 1. The thrusters are placed in a 2x2 grid with a center-to-center separation of 115 mm.

Each BHT-200 in the cluster is independently connected to four power supplies. A Sorensen DHP-400-5 is used for the main discharge, a Sorensen DCS-600-1.7E is used to power the cathode keeper, and two Sorensen DLM-40-15 provides power to the cathode heater and cathode heater. During all testing the thruster was run at the nominal conditions shown in Table 1. Following exposure of the thrusters to ambient atmospheric conditions, the cathodes of each thruster are conditioned by flowing 1 sccm (98 $\mu\text{g/s}$) of xenon and heating for approximately 90 minutes.

Table 1: Thruster Operating Parameters

Anode flow	840 $\mu\text{g/s}$
Cathode flow	98 $\mu\text{g/s}$
Anode potential	250 V
Anode current	0.83 A
Keeper current	0.50 A
Magnet current	1.0 A
Heater current	3.0 A

An inductive-capacitive ($L = 250 \mu\text{H}$, $C = 13 \mu\text{F}$) filter is placed between the anode and cathode external to the chamber. This filter approximately duplicates the impedance characteristics of a power processing unit (PPU) for the BHT-200. The aim of the circuit in this work is not to attempt to replicate PPU characteristics, but to provide isolation of the power supplies from the discharge oscillations of the plasma and to insure that the oscillations measured are not a product of feedback between the power supplies and the plasma.

Xenon propellant (99.995%) flow to the thrusters was metered by use of Unit Instruments model 7301 mass flow controllers (MFC) calibrated for xenon. Flow for each anode and cathode is individually metered through a separate MFC. Ten thruster electrical operating parameters are recorded during operation of the system using an Agilent 34970A data acquisition and switch unit. These parameters include the currents and potentials of the anode, cathode, heater, keeper, and magnet circuits. These data are taken at approximately 1 Hz.

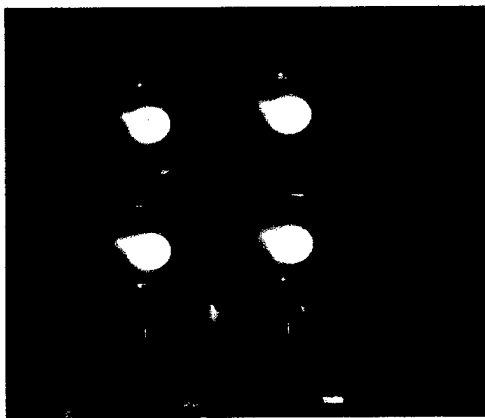


Fig 1. The cluster of BHT-200 Hall thrusters firing within AFRL Chamber 6. The thrusters are numbered 1 through 4 starting from the upper left corner and proceeding counter-clock-wise.

Experimental Results

Figure 2 shows a typical trace of the anode current during a start after the chamber has been open to atmosphere. The initial anode current spike (1.5 A) is due to the start procedure where the anode is current limited and the magnet is off. After the magnet current is switched to its nominal value, the transient consists of anode currents as much as 50% greater than the nominal value of 830 mA lasting approximately 300 to 500 seconds. The anode current transient only occurs for the first 300-500 seconds and does not return on start after the thruster has been conditioned. With subsequent exposure, the transient returns. Figure 3 shows that this behavior persists if the thruster anode discharge is cycled during the time period associated with the anomaly. Interestingly, the thrust level during the period of the anode current transient is unchanged. The 50% increase in anode current simply reduces the efficiency by a like amount.

The effect shown in Figs. 2 and 3 occurs under two distinct circumstances. First, it occurs when the chamber has been opened to atmosphere, exposing the thrusters to ambient air. Second, it occurs when the chamber pumps have been turned off, allowing the cryo-panels to regenerate, exposing the thrusters to a 0.5 Torr 'dirty' vacuum. In the latter case, the cryo-pump is valved off from the chamber, then it and the cryo-panels are allowed to warm to room temperature. The chamber pressure rises to approximately 0.5 Torr (N_2). The atmosphere within the chamber is assumed to consist of primarily xenon gas sublimated from the cryo-panels and water which was trapped by the panels during the initial pump down. However, molecular oxygen can be pumped by the cryo-panels at 25 K, so there may be substantial oxygen and nitrogen in the chamber as well [5]. The atmosphere within the chamber during this conditions will be sampled in future tests. Subsequent use of the chamber does not require repressurization to atmosphere. The chamber may be roughed to approximately 30 mTorr (N_2) at which time the cryo-pump and cryo-panels are activated.

The duration of the anomalous anode current transient appears to depend on the degree of exposure to the atmosphere, or gases sublimated from the pumping surfaces. If exposed to atmospheric conditions for several days, the anode current will return to the nominal 830 mA within 500 seconds. Subsequent exposures to the regenerated vacuum appear to reduce the length of the anode current transient by approximately 20%. For example, thruster 1 was started after exposure to atmosphere and the initial transient persisted for 425 seconds. The chamber was cycled without being opened to atmosphere and the subsequent current transient lasted 340 seconds. This chamber was again cycled without being opened and the anode current transient persisted for only 255 seconds. This trend is typical of all four thrusters in this study.

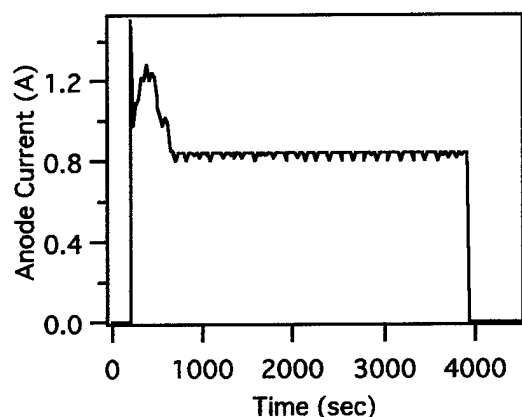


Fig. 2. Anode current trace characteristic of a start following exposure of the thruster to atmospheric conditions for several days. Duration of the anode current transient is 420 seconds. Note: initial current spike to 1.5 A is caused by start-up sequence.

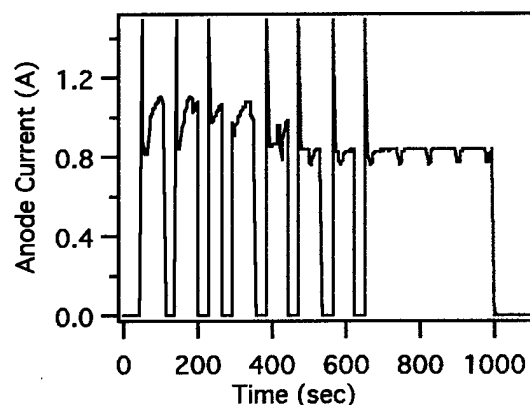


Fig. 3. Anode current trace of the transient with a number of nominally 60 second firings spaced 30 seconds apart. The anomaly persisted for approximately 4.25 min. Note that the thruster has been exposed to regenerated cryo-panel products for a period of 12 days and not exposed to atmosphere.

There are actually two effects shown in Figs. 2 and 3. The anode current transient is accompanied by a periodic (~60 sec) dip in the anode current. Figure 3 shows quite clearly that this period is not affected by the thruster on/off condition. This behavior has been correlated to the pressure fluctuations in the propellant lines of the thruster. The general effect has been documented previously [6]. Due to the low flow of propellant from the pressure bottle through the MFC, the bottle pressure regulator is opening causing a pressure increase in the lines between the regulator and the MFC. The valve on the regulator then closes until the pressure drops by some fraction of the set pressure and then the process repeats. The MFC responds to these periodic increases

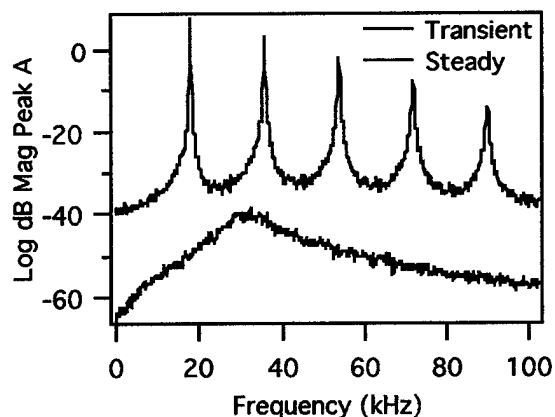


Fig. 4. Two spectra of current oscillations. The first during the transient with an average current of 1.14 A, and the second during steady state operation with an average current of 0.84 A.

in upstream pressure and overcompensates, reducing the flow rate. This overcompensation is due to the flow sensing element being upstream of the throttling valve in the MFC. The MFC does not recognize that it has over compensated and for approximately 3 seconds the flow is reduced by approximately 10%, reducing the anode current by a similar fraction. Efforts are underway to eliminate this issue.

The frequency of the anode current oscillations during a start were measured using Tektronix TCP202 current probes and an TEK1103 probe power supply connected to an Stanford Research Systems SR785 dynamic signal analyzer (DC-104 kHz). A plot of the oscillatory behavior during the anode current transient given in Fig. 4 and compared to the steady state behavior. During the period of anomalous anode current, we see a strong frequency response at approximately 18 kHz and what appear to be 4 harmonics. This behavior is radically different than the steady state behavior also shown in Fig. 4. In the steady state case, there is only a single broad peak at approximately 25 kHz. The steady state spectra is significantly less energetic with peak magnitudes approximately 20 dBA less than the transient case shown in Fig. 4.

Figure 5 shows the time evolution of the anode current frequency spectrum. Although the frequencies of the major features are increasing slightly and the higher orders are decreasing in magnitude, these frequency components retain significant power until they collapse into the steady state single broad peak at 25 kHz. The periodic shifts in the peaks correspond to periods of lowered propellant flow during the pressure regulator approximately 60 second cycle.

The behavior during these two different modes of operation are very different. Examination of the time domain behavior of the anode current using two Tektronix TCP202 current probes connected to a TDS3012 100 MHz bandwidth

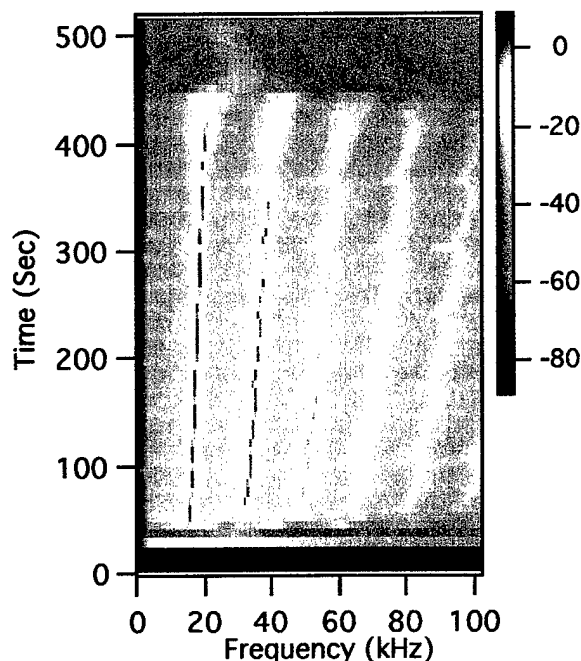


Fig. 5. Contour plot showing the time evolution of the anode Log Magnitude Peak Current (dBA) during a start where the anode current transient is present.

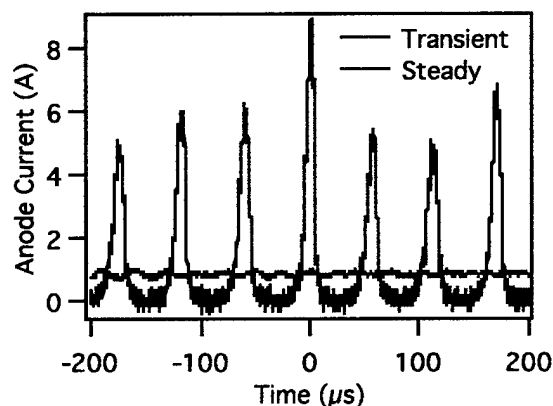


Fig. 6. Current oscillations of the transient and steady state cases seen in the time domain. Conditions are analogous to those in Fig. 4.

oscilloscope. Figure 6 shows the difference between the steady state behavior and the behavior during the anode current transient. During steady state, there is a strong DC anode current component overlaid by a weak 25 kHz component. The behavior during the anode current transient is nearly the opposite. The anode current is primarily AC with peaks measured as high as 9 A. In this mode of operation, the thruster is literally turning itself on and off every 50-60 μ s.

The effect of the LC filter is shown in Fig. 7 where we see the current measured at the thruster compared to the

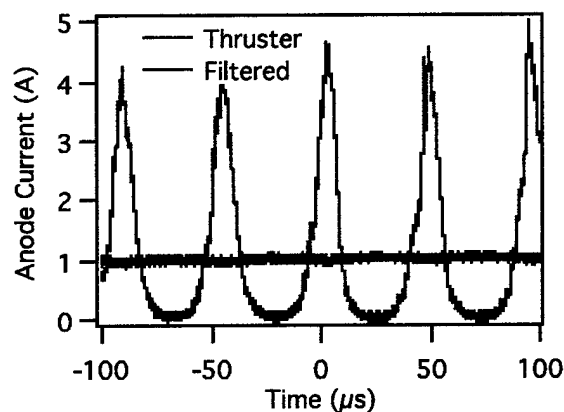


Fig. 7. Current oscillations during the anode current start transient as seen at the thruster and behind the filter at the power supply.

current trace on the power supply side of the filter. The thruster anode sees 18 kHz on/off behavior, while the power supply does not see the oscillations. The LC circuit shields the power supplies exposure to the oscillations by 30 to 50 dB. The use of the LC circuit is not strictly necessary since the inherent impedance of the power supplies produces a similar filtering. Here, the filter is used to provide an additional degree of isolation.

Previously, it has been suggested that the start anomaly is due to the thruster insulator being cleaned by divergent propellant ions impacting channel walls [7]. Those researchers used diffusion pumped vacuum facilities. The concern was that the anomaly was due to backstreamed pump oil, or sputtered materials from vacuum chamber surfaces. In this case, we were not willing to rule out the possible contribution of the cathode, especially in light of the on/off behavior shown in Figs. 6 and 7.

To explore the possible oxidation of the cathode and/or anode, two tests were conducted. In each test, two thrusters were operated until the anomalous anode current was eliminated and the thrusters were said to be conditioned. Each was subsequently restarted to confirm steady state operation. One of the two conditioned thrusters was designated a control and purged with 5 and 9 sccm xenon flow through the cathode and anode, respectively.

In the first test, the propellant line to the anode was opened to ambient laboratory air (25°C, 21% relative humidity, 670 Torr). The flow was manually metered by monitoring the pressure rise within the chamber so that it did not rise above 5×10^{-5} Torr. The air flow, estimated at 30-40 sccm, continued for approximately 10 min. The air flow was then stopped and the anode propellant line reconnected. The propellant lines were then flushed with xenon to eliminate residual oxygen in the lines. Subsequently the thruster and control

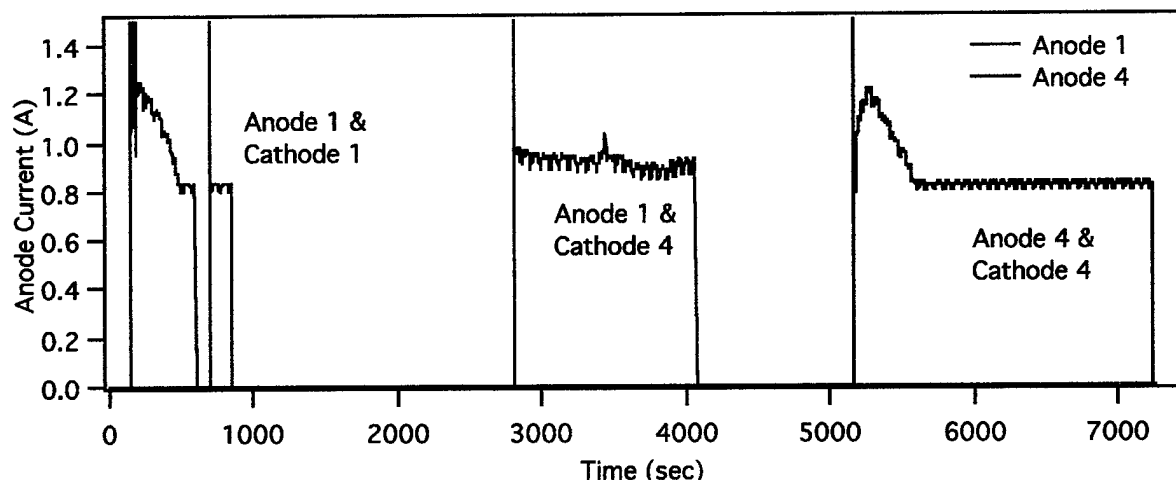


Fig. 8. Firing of anode 1 with cathode 1 and cathode 4 compared to the firing of anode 4 with cathode 4. Note that when anode 1 is fired with cathode 4, the coupling of the anode cathode is inferior to the nominal case, presumably since cathode 4 is not adjacent to anode 1.

were individually started. Neither exhibited the anode current transient.

In the second test, the propellant line to the cathode was opened to ambient air similar to the first test. After the cathode's exposure to atmospheric air, the cathode line was reconnected and flushed. In addition, the cathode was reconditioned by flowing 1 sccm of xenon and operating the heaters at reduced power for 90 min. This is the standard procedure prior to all operations following exposure to atmosphere, as such we did not feel this impacted the tests validity. As in the first test, neither the cathode of the exposed thruster, nor the conditioned control exhibited any signs of the anode current transient.

In a subsequent test, all four thrusters of within the vacuum chamber were fired until conditioned. The thrusters were all turned off and the cathode of thruster 2 was purged with 3 sccm of xenon, the anode thruster 3 was purged with 9 sccm of xenon. Thrusters 1 and 4 were kept as controls. The chamber was allowed to regenerate overnight and was restarted in the morning. The result of this test was that all four thrusters exhibited identical and typical anode current anomalies similar to that shown in Fig. 2.

As a result of the first three tests, the anode current transient had not been isolated to either the cathode or the anode; however, the effect did appear to require significant exposure time (hours) to manifest itself. The conclusive test was performed by taking advantage of the cluster of four Hall thrusters and their relative proximity within the vacuum facility. In this test, two unconditioned, adjacent thrusters, 1 and 4, were fired in the following sequence. First, thruster 1 was started using cathode 1, and fired for a sufficient time to condition the thruster. Then, the thruster was shut down and

restarted briefly to confirm its conditioning. At this time, cathode 4 (the cathode nominally attached to thruster 4) was substituted electrically for cathode 1. Anode 1 with cathode 4 was subsequently started. At this time, no anode current anomaly was detected. As a control, cathode 4 was electrically reconnected to anode 4 and fired. This resulted in a typical example of the anode anomalous behavior. The anode currents measured during this sequence are illustrated in Fig. 8.

Analysis

The result of this testing eliminates the cathode as the source of the anode current transient, and points definitively at the main discharge. An examination of the main discharge chamber of the Busek BHT-200-X3 Hall thruster, or any other similar Hall thruster, reveals that the portions of the thruster wetted by the plasma are limited to the alumina plasma sprayed coated front plate of the magnetic circuit, the anode, and the boron nitride acceleration channel insulators.

Of these three, the most likely culprit is the boron nitride (BN) inserts due to their high porosity (~15%) and its thermodynamic tendency to hydrate with incident water. Some BN grades are capable of absorbing up to 3.5% of their weight in water in conditions of high relative humidity. Grades usually associated with Hall thrusters generally absorb less water (<1%). No data on the depth of penetration is known. The hydration is believed to be primarily a surface phenomena and the depth of penetration is likely less than 100 μm . The hydration of BN may be reversed by heating. For example, Saint-Gobain suggests heating their product to approximately 400°C for one hour to reverse hydration caused by exposure to atmospheric water vapor.

What appears to be occurring is the plasma within the acceleration channel is either etching away the hydrated layer of the insulator, or heating the hydrated surface and driving the water out of the BN matrix. The impact of relatively high energy xenon ions into the wall is changing the insulator wall properties. Some wall materials are certainly etched, but ion recombination energy (12.1 eV) as well as kinetic energy (0-200 eV) will be deposited on the wall surface by each ion impact, substantially heating the surface layer. Despite the high thermal conductivity of BN, any given area of the accelerator channel wall will be periodically heated to very high temperatures which result in water molecules being driven from the BN matrix. Considering the time scale of 300-500 seconds, this appears to be the most likely scenario.

The most surprising result is the difference in the acceleration channel current conduction between the anode current transient and steady state. These two cases represent distinct operating conditions. In steady state operation, the small amplitude approximately 25 kHz frequency component is generally attributed to the so-called 'breathing mode' oscillation [8]. Here, the ionization occurs in a planar sheet which oscillates transversely within the acceleration channel. The frequency of which is related to the neutral residence time (25 kHz \rightarrow 40 μ sec). During the anode current transient, an amplified breathing mode oscillation appears to dominate the main discharge.

The question that this effort has not answered is how to relate the change in mode of operation, particularly of the plasma oscillations to the material properties of the BN acceleration walls. The most likely reason for the anomalous anode current transient is that the secondary electron yield of the acceleration channel walls is modified by hydration, or alternatively, by the de-hydration of the wall in the first 300-500 seconds of operation following exposure of atmospheric conditions. Modification of the secondary electron yield would affect near wall conductivity through the radial magnetic field. Changes in the near wall conductivity could then lead to changes in the acceleration channel oscillations which are considered the primary cross-field electron conduction path [9]. If this is the case, then the modification of the near wall conductivity has significantly altered the characteristic electron conduction through the radial magnetic field.

Since during the transient period the anode current is seen to increase, then decrease, the process may be more complex than merely the modification the secondary electron yield on the walls. An alternative explanation may be that the release of water into the acceleration channel is affecting the discharge. The presence of hydrogen ions (protons) formed by disassociation of water molecules could be affecting the discharge. If protons are produced in the high magnetic field

regions of the acceleration channel, their Larmor radii (assuming $B = 200$ G, $T = 300$ K) would be on the order of 1-2 mm where the Larmour radius is given by [10],

$$r_L = \sqrt{\frac{8kTm}{\pi q^2 B^2}} \quad (1)$$

where k is the Boltzman constant, T is the temperature, m is the particle mass, q is the particle charge, and B is the magnetic field strength. The dependencies of Eqn. 1 are such that the Larmor radii of positive hydrogen ions will be an order of magnitude less than those of xenon ions (assuming comparable temperatures). The hydrogen ions will be magnetized to a much greater extent than xenon. It is possible that the introduction of small amounts of positive ions trapped in the high electron density region of the acceleration channel with Larmor radii of similar size to the those of the electrons could produce plasma instabilities that produce an enhanced breathing mode oscillation. A previous study has shown that the introduction of hydrogen into the acceleration channel increased plasma oscillations, so this possibility merits further investigation [11].

Conclusions

It is important to realize that the anomalous anode current transient examined in this work is only of interest during initial Hall thruster operation. Its effect is generally neglected in the laboratory for good reason. The transient only occurs within the first 500 seconds of operation after exposure to what we believe to be atmospheric water vapor which is absorbed in the surface of the boron nitride acceleration channel insulator. After the thruster has been conditioned, subsequent restarts do not exhibit the anode current transient.

For many on-orbit operations, this transient can also be neglected. Station keeping systems with lifetimes of thousands of hours may neglect the first 500 seconds of degraded performance. The systems that cannot neglect this behavior are smaller satellite systems which are launched en-masse. These systems require short duration firings with known impulses to accurately place formations of satellites into precise orbits. The increasing interest in the space community in distributed architectures of small satellites indicates that the importance of this issue will increase.

Another issue where the anomalous anode current transient is an issue is in the clustering of Hall thrusters in close proximity. As presented elsewhere, the greatest interaction of a number of independent thrusters clustered together in close proximity is during the anode current transient [4].

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